Effects of force load, muscle fatigue and magnetic stimulation on surface electromyography during side arm lateral raise task: a preliminary study with healthy subjects

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Abstract

The aim of this study was to quantitatively investigate the effects of force load, muscle fatigue and extremely low frequency (ELF) magnetic stimulation on surface electromyography (SEMG) signal features during side arm lateral raise task.

SEMG signals were recorded from 18 healthy subjects on the anterior deltoid using a BIOSEMI Active Two system during side lateral raise task (with the right arm 90 degrees away from the body) with three different loads on the forearm (0kg, 1kg and 3 kg; their order was randomized between subjects). The arm maintained the loads until the subject felt exhausted. The first 10s recording for each load was regarded as non-fatigue status and the last 10s before the subject was exhausted as fatigue status. The subject was then given a five-minute resting between different loads. Two days later, the same experiment was repeated on every subject, while this time the ELF magnetic stimulation was applied to the subject's deltoid muscle during the five-minute rest period. Three commonly used SEMG features, including root mean square (RMS), median frequency (MDF) and sample entropy (SampEn) were analyzed and compared between different loads, non-fatigue/fatigue status, and with/without ELF magnetic stimulation.

Variance analysis results showed that the effect of force load on RMS was significant ($p<0.001$), with increased RMS observed with the increase of force loads, but not for MDF and SampEn (both $p>0.05$). In comparison with non-fatigue status, for all the different force loads with and without ELF stimulation, RMS was significantly larger at fatigue (all $p<0.001$) and MDF and SampEn were significantly smaller (all $p<0.001$). Furthermore, variance analysis showed that force and fatigue had significant interaction on RMS change ($p<0.001$), but not on MDF and SampEn ($p>0.05$). Finally, the RMS, MDF, SampEn and their changes with force were not significantly different between with and without ELF stimulation (all $p>0.05$).

Our study comprehensively quantified the effects of force, fatigue and the ELF magnetic stimulation on SEMG features, which may facilitate a better understanding of the underlying physiological mechanisms of muscle activities associated with force and fatigue, and of muscle physiological response to ELF magnetic stimulation.

Keywords: Extremely low frequency (ELF) magnetic stimulation; Fatigue; Force; Lateral raise task; Surface electromyography (SEMG)

1. Introduction

Surface electromyography (SEMG) is a non-invasive technique to measure muscle electrical activity during muscle contraction, which can reflect the functional status of muscles. It has been widely used by clinicians as a diagnostics tool to identify neuromuscular diseases and disorders of motor control, and to evaluate and monitor rehabilitation program [1].

SEMG is composed of action potentials from groups of muscle fibers organized into motor units (MUs), and therefore contains information about the characteristics and physiology of the active MUs [2]. The amount of force produced by a muscle depends on the MU activation patterns and the mechanical properties of the muscle fibers [3, 4]. Isometric contraction tasks such as hand grips have been applied to investigate the relationship between SEMG and force load of the upper limb [5, 6]. However, the handgrip task is not easy to perform for stroke patients with upper extremity movement disorder. Similar to the handgrip task, the side arm lateral raise task also generates isometric contractions, in which muscles generate tension without changing muscle length [7]. It is expected that performing the side arm lateral raise task could be easier in developing alternative rehabilitation programs to alleviate physical fatigue for stroke patients in comparison with handgrip task. This provides the clinical rationale of this preliminary study with healthy subjects.

Many physiological properties of the muscle, including the number of MUs, the peak discharge rates and MU synchronization etc. are also affected by fatigue and peripheral stimulation [8, 9].

Muscle fatigue occurs after a prolonged or repeated muscle activity with a failure to maintain the required or expected force [10]. The degree of muscle fatigue can be measured by a relative maximal voluntary force loss during sustained contraction tasks [11, 12]. Muscle fatigue has been considered as one of the risk factors for musculoskeletal problems [13], which is one of the most difficult sequelae to adjust for many stroke patients who suffer from fatigue. Moreover, during rehabilitation process, fatigue may impair the patients' ability to regain muscle functions loss. Clinically, the perceived muscle fatigue has been used to evaluate the effectiveness of post-stroke training program [14-16]. Although there was no clinically accepted indicator to assess fatigue, it has been reported that muscle fatigue leads to recognizable degradation of SEMG pattern [17]. It is therefore clinically useful to further investigate the relationship between muscle fatigue and SMEG feature change.

Low-intensity low-frequency magnetic stimulation has been shown to induce neuro modulation in humans without causing any pain [18, 19]. However, most of the previously published work applied the transcranial magnetic stimulation on the brain to alter human motor cortex excitability [20, 21]. It has been reported that extremely low-frequency (ELF, 3-30Hz）pulsed electromagnetic field induced accelerated regeneration with injured peripheral nerves in rats [9, 22]. Although the peripheral magnetic stimulation has been studied recently, it has not been applied on human subjects [23, 24]. Therefore, the investigation on the effect of ELF magnetic stimulation on SEMG signal could provide preliminary evidence for a better understanding of the muscle activity.

Previous studies have investigated the separate relationships between SEMG signal and force, and between SEMG features and neurophysiology of muscle fatigue [25-27], however, there were no comprehensive studies to investigate the combinational effect of force load, muscle fatigue and magnetic stimulation on SEMG, particularly during the side arm lateral raise task.

To analyze the changes of SEMG signal with muscle force and fatigue, various SEMG signal characteristics, including amplitude-based features, spectral features, time-frequency features and non-linear features of SMEG, have been analyzed during muscle contraction [28-30]. Root mean square (RMS) represents the signal power in the time domain and has been used to measure the level of activation of a muscle [8, 31]. Median frequency (MDF) is an indication of muscle fatigue in the frequency domain during isometric contraction [8]. It has been reported that the decrease of MDF and the increase of SEMG signal amplitude are good indicators of fatigue [32]. As a measure of complexity due to the stochastic behavior of SEMG, sample entropy (SampEn) is related to the MUs recruitment and their firing rate [8, 25]. Moreover, RMS, MDF and SampEn of SEMG signals have already provided meaningful evidence in association with physiological mechanisms during the muscle contractions [33, 34]. These features were therefore selected in this study, which in general reflect the amplitude, frequency and non-linear features of SEMG signals.

This study therefore aimed to quantitatively investigate the effects of different force loads on the RMS, MDF and sample entropy derived from SEMG signals during the side arm lateral raise task, and to compare the different effects between fatigue and non-fatigue status, and between with and without ELF magnetic stimulation. The experiment will be conducted on healthy adults in this study to provide preliminary evidence for future development of alternative rehabilitation programs for alleviating physical fatigue.

2 Materials and methods

2.1 Subjects

18 healthy male subjects (aged 25±3years) without any known history of neurological or psychiatric disorders were recruited. All subjects were right-handed, according to the Oldfield's Edinburgh inventory (Oldfield, 1971). Informed and written consent was obtained from each of the subjects after the aims, potential benefits and risks were explained. The study was carried out according to the Declaration of Helsinki (1989) of the World Medical Association, and approved by the Local Ethics Committee of Beijing University of Technology.

2.2 Experimental procedure

During the experiment, the subjects were asked to sit comfortably with the right arm side lateral raise (90 degrees away from the body) as shown in Fig.1. Different loads (0 kg, 1 kg or 3 kg) were wrapped up on the forearm with a black bandage to generate isometric force at the upper limb muscle. The sequence of the loads was randomized among the subjects.

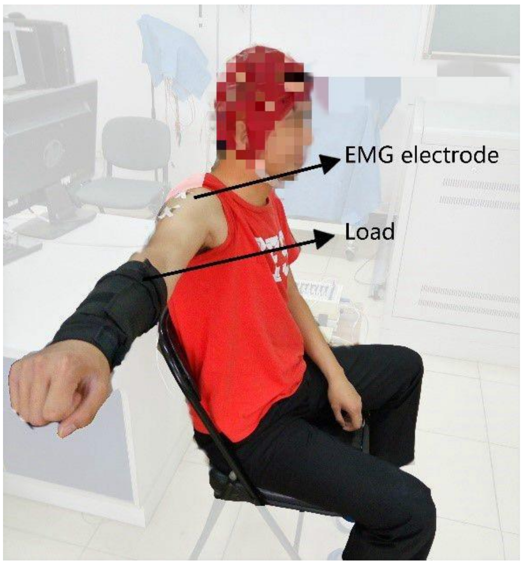

Fig.1: Illustration of lateral raise task with a subject sitting on a chair.

It has been suggested by clinicians that the anterior deltoid plays an important role in maintaining the lateral raise [7]. Therefore, SEMG signals were collected from the anterior deltoid of the right arm using flat-tape active-electrodes attached to the skin. While the arm was laterally raised with a load, SEMG signals were recorded by a BioSemi ActiveTwo (BioSemi, Netherlands) system with a sampling frequency of 1024Hz until the subject felt exhausted. He was then given a five-minute rest between different force loads. The same procedure was repeated three times with a total 9 SEMG recordings, as shown in Fig.2 (a).

Two days later, the same experiment was conducted with additional 9 SEMG signals. This time, an ELF magnetic stimulation was applied to the subject's deltoid muscle during the five-minute resting period.

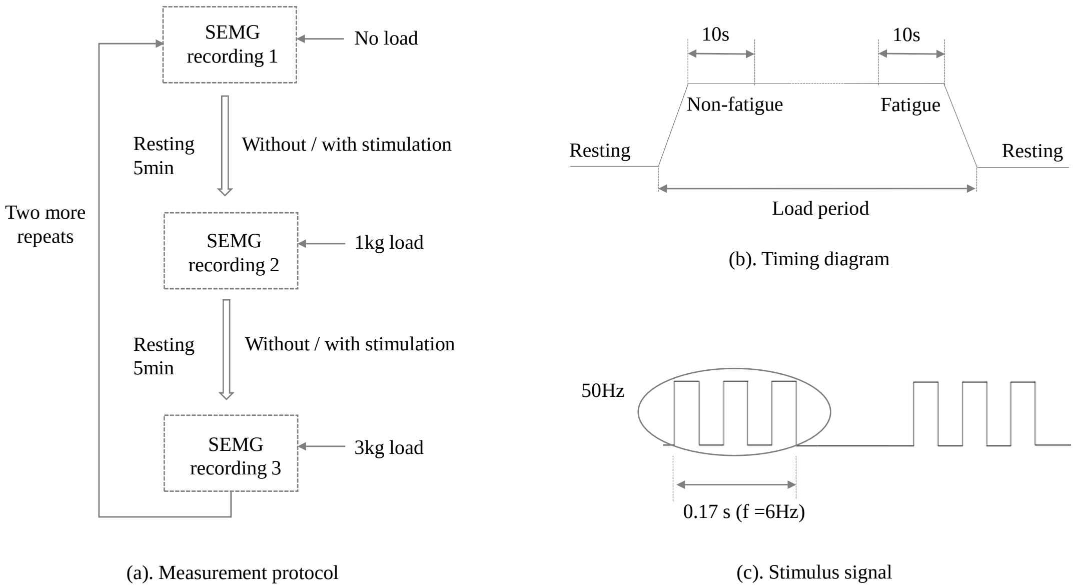

Fig.2: Measurement protocol, timing diagram of the recorded SEMG signal and stimulus signal.

2.3 Magnetic stimulation device

The magnetic stimulation device was developed in our lab with a four-circular coil. The stimulus signal was generated and driven by an ARM microprocessor and power amplifier. The intensity and frequency of stimulation were adjustable between 10-40mT and 1-10Hz, respectively. In this study, their corresponding values were 30mT and 6Hz. There were three 50Hz pulses within each simulation cycle, and its duty cycle was 50%, as shown in Fig.2(c).

2.4 SEMG signal pre-processing

The recorded SEMG signals from a pair of electrodes were differentially processed. For the SEMG signal recorded at a certain load on the arm, the first 10s recording was regarded as non-fatigue status and the last 10s period before the subject was exhausted as fatigue status, as shown in Fig.2 (b). The two segments of 10s SMEG signals were then extracted for further analysis.

The interference (raw) EMG contains main frequency from 10~300 Hz [35, 36] and the low frequency components of EMG are related to activation of a muscle [37]. Therefore, the surface EMG signals in our study were pre-processed using a 1~300 Hz band-pass filter and a 50 notch filter to remove noise. Current source density transformations were then applied to reduce the effect of volume conduction on SEMG signals.

2.5 SEMG feature calculation

Three commonly used SEMG features (RMS, MDF and SampEn) were calculated in this study.

Root mean square (RMS)

RMS was calculated as

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\sum\nolimits_{n} x_n^2} \tag{1}$$

where x_n is the value of SEMG signal, and n is the number of samples. Here n= 2048 in this study.

Median frequency (MDF)

MDF is the frequency value that separates the power spectrum in two parts of equal energy [38]. It was calculated by:

$$f_{med} = i_m \frac{f_s}{N}, \qquad \sum_{i=0}^{i=i_m} P(i) = \sum_{i=i_m}^{i=N-1} P(i) \tag{2}$$

Power spectra density P was calculated by the method of averaged periodogram. The 10s SEMG signal sequence (x(n), n=0, 1, … , N-1) was divided into K segments with J samples overlapping, and each of the segment had L samples. The recording was subdivided as: $x_i(n)=x(n+i(L-J))$, i=0, 1, …, k-1, n=0, 1 , …, L-1. In this study, N=10240, L=2048, K=5, J=1024.

Sample entropy (SampEn)

Entropy is a non-linear measurement of the complexity of SEMG signal. For a given embedding dimension m, tolerance r and number of data points N, SampEn(m, r, N) is the negative logarithm of the probability that if two sets of simultaneous data points of length m have distance<r then the two sets of simultaneous data points of length m+1 also have distance<r.

For the time-series SEMG of length N= $\{x_1, x_2, x_3, \ldots, x_N\}$with a constant time interval τ, we defined a template vector of length m, such that $X_m(i)=\{x_i, x_{i+1}, x_{i+2}, \ldots, x_{i+m-1}\}$ and the distance function $d[X_m(i), X_m(j)](i \neq j)$. We counted the number of vector pairs in template vectors of length m and m+1 having $d[X_m(i), X_m(j)]<r$ and denoted it by B and A respectively. The sample entropy was defined as:

$$SampEn= -\log(A/B) \tag{3}$$

where A = number of template vector pairs having $d\,[X_{m+1}(i), X_{m+1}(j)]<r$ of length m+1,

B= number of template vector pairs having $d\,[X_m(i), X_m(j)]<r$ of length m.

The value of m was set to be 2 and the value of r to be 0.2×stand deviation (SD) from 18 subjects at the same status. It could be seen from the definition that A has a value smaller or equal to B. Therefore, SampEn (m, r, N) is always either be zero or positive value. A smaller value of SampEn indicates better self-similarity in SEMG.

2.6 Data and statistical analysis

The mean, standard deviation (SD) or standard error of the mean (SEM) of lateral raise task duration (the endurance time with a load until he was exhausted) and the SEMG signal features (RMS, MDF and SampEn) were calculated across all the subjects, separately for different force loads, for the fatigue/non-fatigue status and without/with ELF magnetic stimulation. Analysis of variance was performed using SPSS 22 (SPSS Inc.) to assess the measurement repeatability and the effect of force, fatigue and magnetic stimulation on SEMG features, with their difference between forces, fatigue/non-fatigue, and with/without stimulation compared. A P-value below 0.05 was considered statistically significant.

3. Results

3.1 Lateral raise task duration with force

The raise duration varied between subjects and with different force loads. As shown in Fig.3, the lateral task duration decreased significantly with the increase of force loads ($P<0.001$). However, the duration was not significant difference with and without stimulation ($P>0.05$).

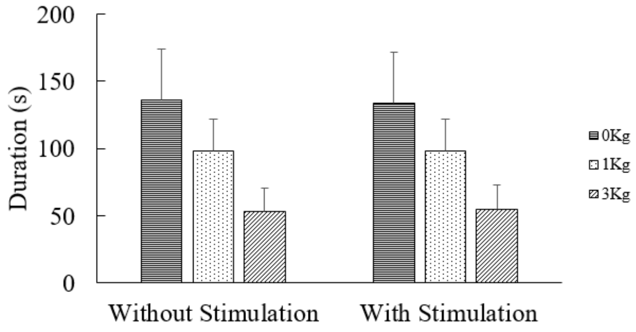

Fig.3: Lateral raise task duration with different force loads, separately between with and without ELF stimulation. The data was presented as mean ± SD.

3.2 Measurement repeatability of RMS, MDF and SampEn of SEMG

ANOVA analysis showed there was no significant difference between the three repeated measurements for all the SMEG features derived in this study (all P>0.05), demonstrating the reliability of the experimental setup. Therefore, the different features from the three repeated measurements were averaged for further analysis.

3.3 Effect of force on RMS, MDF and SampEn of SEMG

ANOVA analysis showed that the effect of force loads on RMS was significant ($p<0.001$). As shown in Fig. 4, under both conditions (with and without magnetic stimulation), the RMS increased significantly with force at both non-fatigue and fatigue status (both $p<0.001$). The SampEn decreased significantly with force only at non-fatigue status ($p<0.05$). However, as a whole, the effect of force on MDF was not significant (both $p>0.05$).

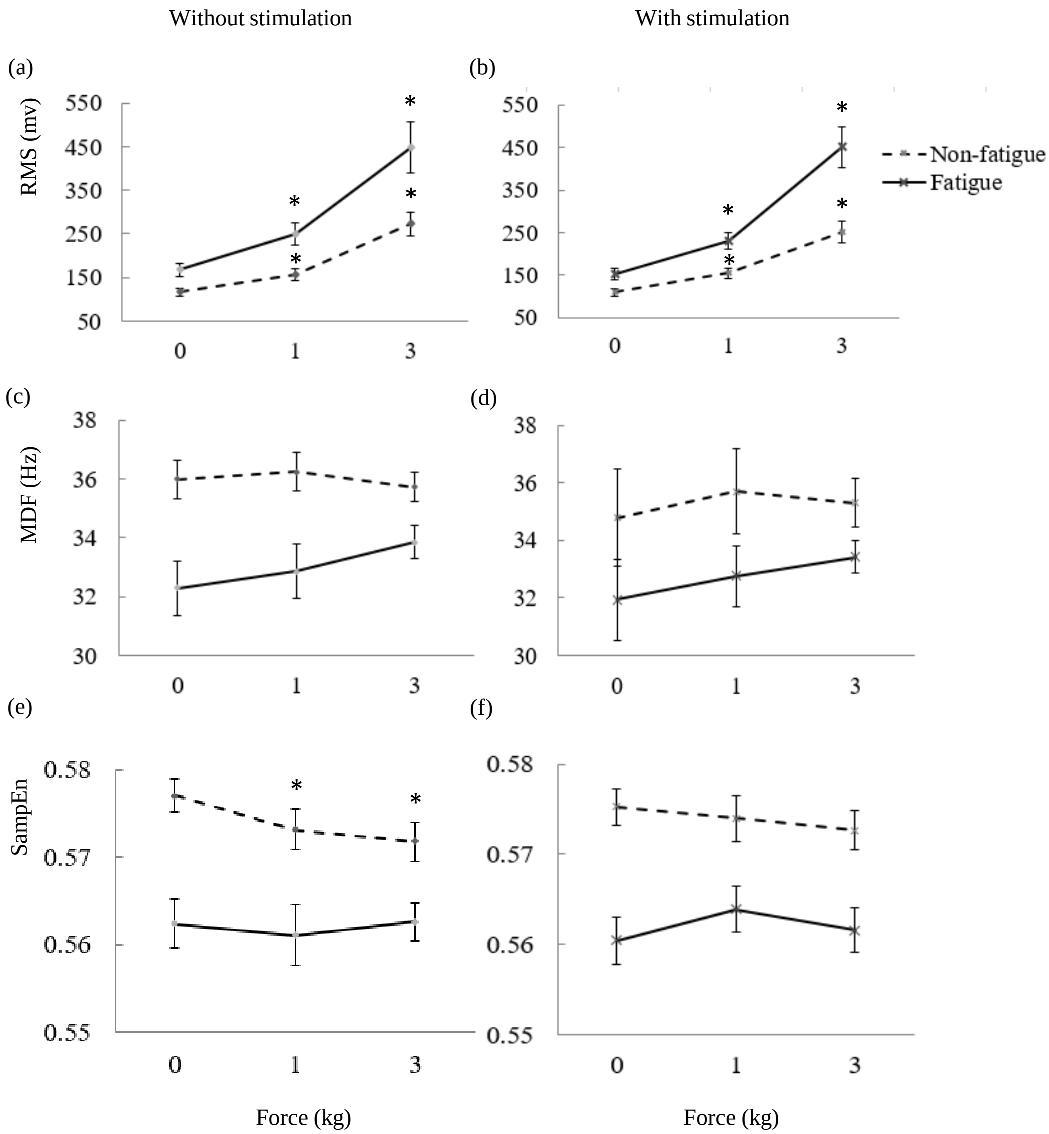

Fig.4 Mean ± standard error of the mean (SEM) of RMS, MDF and SampEn with different force loads, separately for between fatigue and non-fatigue, and between with and without ELF stimulation (*: Significantly different when compared with zero force).

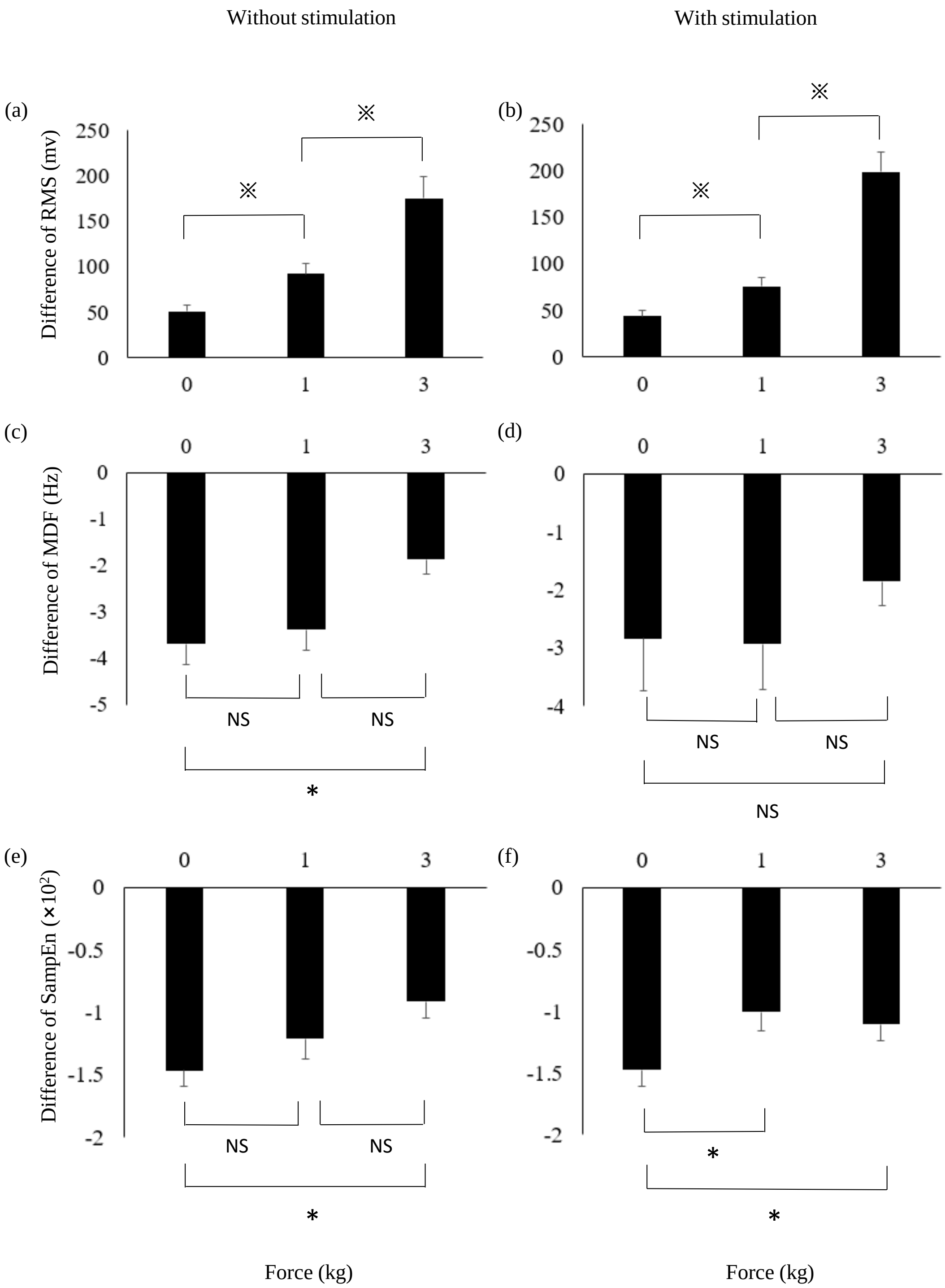

Fig.5 Differences (mean+/- SEM of difference) of RMS, MDF and SampEn of SEMG between fatigue and non-fatigue, separately for different force loads, and between without and with ELF magnetic stimulation (※: $p<0.001$; *: $p<0.05$; NS: No significant difference).

3.4 Comparison between fatigue and non-fatigue status

The differences of RMS, MDF and SampEn of SEMG signals between fatigue and non-fatigue status are shown in Fig. 5, separately for different force loads, and between without and with stimulation. Under both conditions (with and without ELF magnetic stimulation), the RMS at fatigue was significantly larger than non-fatigue (all $p<0.001$), whereas MDF and SampEn at fatigue were significantly smaller than non-fatigue (all $p<0.001$).

More importantly, the RMS difference between fatigue and non-fatigue gradually and significantly became larger with increasing load forces (both $P<0.001$ for the comparison of RMS difference between 0 and 1 Kg force, and between 1 and 3 Kg force loads), indicating that the force and fatigue had interactions on RMS. This has also been confirmed in the two-way ANOVA analysis that force and fatigue had significant interaction on RMS change ($P<0.001$). However, there were not significant interactions for the MDF and SampEn of SEMG (both $p>0.05$).

3.5 Comparison of different force and fatigue effects on SEMG features with and without ELF stimulation

The three SEMG features (RMS, MDF, SampEn), their changes with force and their differences between fatigue and non-fatigue were not significantly different between with and without ELF magnetic stimulation (all $p>0.05$).

4. Discussion and conclusion

This study investigated the effect of force, fatigue and ELF magnetic stimulation on SEMG signal features (including RMS, MDF and SampEn) from the SMEG signals recorded with different force loads applied on the forearm during the lateral raised task. To the best of our knowledge, this is the first comprehensive study to quantify these effects.

As expected, the lateral raise task duration decreased with increased force loads on the arm. Although 60-70% of the subjects improved their endurance after ELF stimulation, the raise duration was not significantly different between with and without magnetic stimulation. One of the possible reasons might be that a larger sample size is needed in this experiment.

An objective and non-invasive assessment of muscle activity can be indicated by SMEG feature changes with different force loads. It is known that SEMG consists of the weighted sum of the electrical contributions of active MUs, and therefore contains information about the characteristics and physiology of the active MUs including its activation and firing rates. During voluntary muscle contractions, the modulation of the firing rates of existing active MUs and the recruitment of new MUs are the two main mechanisms responsible for the maintenance of a specific level of force. Both the force exerted by a muscle and the amplitude of the SEMG depend on the number of recruited MUs and the discharge rate of each active MU. A higher muscle contraction level requires the recruitment of more MUs, resulting in higher RMS of the EMG signal [8, 31]. In this study, a statistically significant difference on RMS was demonstrated between different force levels. Therefore, our results agreed with physiological explanation with significantly increased RMS ($p<0.001$) when the force load was increased. Additionally, it was found that there was no significant MDF difference between different force levels. Previous studies showed an increase in MDF of SEMG signals with an increasing level of muscle contraction [39]. However, those studies presented SEMG features at higher level of muscle contraction, and that there are also discrepancies in opinions on MUs firing and recruitment at different levels of contractions. According to DeLuca and Erim’s model, at a low level of muscle contraction, when a low number of MUs is recruited, the component of firing rates frequency in power spectrum density (PSD) is relatively high and more MUs are recruited, lowering the value of MDF [40]. Besides, force level did not affect SampEn of SEMG, indicating that the self-similarity of SEMG has not been changed with different forces. As far as we know, SampEn change with force level has not been studied before.

Muscle fatigue occurred when the subject was unable to maintain force during a sustained muscle contraction. Our work showed that RMS was larger at fatigue, and MDF and SampEn were smaller in comparison with non-fatigue status. This agreed with a published study [40], where it explained that the newly recruited MUs, synchronization of MU firing and decreased muscle fiber conduction velocity (MFCV) could be the possible mechanisms for increased SEMG signal amplitude at fatigue status [27, 41]. At the fatigue status, the drop in motoneuron excitability with sustained muscle activity results in decreased firing rates of active MUs [41] and slower MFCV, leading to MDF shift to lower frequency range. In terms of the results of SampEn, a non-linear measurement of the complexity of the signal of muscle fibers, the lower SMEG signal complexity may be related to an abnormal condition such as fatigue and pathology [30]. At fatigue status, with decreased firing rate of MUs, EMG signals have less stochastic behavior, leading to reduced SampEn. Previous study found that greater entropy corresponded to a broader power spectrum, and smaller entropy corresponded to a peaked power spectrum [30]. SEMG power spectrum becomes more peaked and concentrated in lower frequencies due to physiological mechanisms of muscle fatigue. Therefore, it appears that the entropy can be affected by a physiological mechanism similar to that which affects the median power frequency. This result is in accordance with the finding during isometric fatiguing contraction, where the entropy and median frequency decrease [42].

This study also showed that there was no significant difference in SEMG features and their changes with force between with and without magnetic stimulation, which corresponded to the non-significant difference of raise duration with and without ELF stimulation. Some possible reasons could include: the intensity of ELF stimulation was too weak, the duration of stimulation was not long enough, or the ELF magnetic stimulation itself did not have delay effect on the SEMG signal recorded after the magnetic stimulation. Nevertheless, this study has provided preliminary evidence for future development of alternative rehabilitation programs for alleviating physical fatigue.

It is noticed that there was large inter-individual variability due to different muscle strength between individuals. However, this preliminary study mainly focused on the within-subject comparison between loads, fatigue/non-fatigue and with/without stimulation. Besides, ANOVA analysis showed there was no significant difference in all the SMEG features between three repeated measurements, separately for each load (all $P>0.05$). Therefore, their averages from the three measurements were used for further analysis. In addition, for the two segments (two 10s SMEG signals at non-fatigue and fatigue periods) used for signal processing, it was observed that the signals were quite stable without sharp baseline shift. A better way should be considered to control the experimental setup in further study.

One of the limitations of this study is that the task order (with and without simulation) should be randomized between subjects in the study design. However, it should be acceptable that the effect of the task order (with and without simulation) could be neglected in this particular study because there was a 2 days' interval between the tasks.

Due to the variability of muscle characteristics between individuals, there is no simple way to define a precise muscle fatigue threshold. It is known that the amplitude of muscle contraction is often compared to maximum voluntary contraction (MVC), which can be rescaled to % of MVC. However, considering the potential clinical applications of raising arm, it may not be easy and completely safe to obtain the MVCs from patients with movement disorder. Therefore, to simplify the experimental procedure and reduce the study risks, as a preliminary study, the absolute forces were applied in this study. The absolute forces would impose different challenges between individuals, resulting in different duration of the lateral raise, as shown in the Fig. 3. The different effect of applying absolute force and % of MVC on both healthy subjects and patients could be comprehensively investigated in a future study. Additionally, other parameters with global perspective of the shifting in SEMG frequency may also demonstrate their association with muscle fatigue, leading to potential biological importance. For instance, SEMG power in gamma band (35~60 Hz), can also be investigated in a future study.

In addition, the effect of using different stimulus modes including the waveform, intensity and frequency, could be investigated, as well as the comparison with simultaneous SEMG recording during magnetic stimulation. Finally, as a pilot study, only male subjects were used. In the future, a comparison between male and female subjects is also worthy of further investigation.

In conclusion, our study comprehensively analyzed the effects of force, fatigue and the ELF magnetic stimulation on SEMG features, which may facilitate better understanding of the underlying physiological mechanisms of muscle activities associated with force, fatigue and SEMG response to ELF magnetic stimulation.

Compliance with Ethical Standards: All procedures performed in studies involving human participants were in accordance with the ethical standards of local ethics committee of Beijing University of Technology and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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Informed consent: Informed consent was obtained from all individual participants included in the study.

References

[1] Wolf S, Butler A, Alberts J et al. 2005 Contemporary linkages between EMG, kinetics and stroke rehabilitation. *J Electromyogr Kinesiol*. **15** 229–239.

[2] Karlsson J, Roeleveld K, Grönlund C et al. 2009 Signal processing of the surface electromyogram to gain insight into neuromuscular physiology. *Phil. Trans. R. Soc. A* **367** 337–356.

[3] Doheny E, Lowery M, Fitzpatrick D et al. 2008 Effect of elbow joint angle on force–EMG relationships in human elbow flexor and extensor muscles *J Electromyogr Kinesiol.* **18** 760–770.

[4] Anders C, Brose G, Hofmann G et al. 2008 Evaluation of the EMG–force relationship of trunk muscles during whole body tilt *J of Biom.* **41 (2)** 333–339.

[5] Aoife F, Leonard S 2013 Effects of grip type and wrist posture on forearm EMG activity, endurance time and movement accuracy *Int J Ind Ergon.* **43** 91–99.

[6] Soo Y, Sugi M, Nishino M et al. 2009 Quantitative estimation of muscle fatigue using surface electromyography during static muscle contraction. *31st Annual International Conference of the IEEE EMBS Minneapolis, Minnesota, USA.* 2975-2978.

[7] Widmaier EP, Raff H, Strang KT 2010 "Muscle". *Vander's Human Physiology: The Mechanisms of Body Function* (12th ed.). New York, NY: McGraw-Hill 250–291.

[8] Al-Mulla M, Sepulveda F, Colley M 2011 A Review of Non-Invasive Techniques to Detect and Predict Localised Muscle Fatigue *Sensors* **11** 3545-3594.

[9] Tasset I, Medina F, Jimena I et al. 2012 Neuroprotective effects of extremely low-frequency electromagnetic fields on a huntington's disease rat model: effects on neurotrophic factors and neuronal density *Neuroscience.* **209** 54-63.

[10] Gandevia S 2001 Spinal and supraspinal factors in human muscle fatigue *Physiol Rev.* **81** 1725–1789.

[11] Rong Y, Hao D, Han X et al. 2013 Classification of surface EMGs using wavelet packet energy analysis and a genetic algorithm-based support vector machine *Neurophysiology* **45(1)** 39-48.

[12] Rong Y, Moncel N, Zhang Y et al. 2011 Fatigue muscle detection using time-frequency Methods *4th International Congress on Image and Signal Processing* 2505-2507.

[13] Fimland M, Maen P, Hill T, et al. 2011 Neuromuscular performance of paretic versus non-paretic plantar flexors after stroke *Eur J Appl Physiol* **111(12)** 3041-3049.

[14] Van de Port I, Wevers L, Roelse H et al. 2009 Cost effectiveness of a structured progressive task-oriented circuit class training programme to enhance walking competency after stroke: the protocol of the FIT-stroke trial *BMC Neurol* **9** 43.

[15] Prange G, Jannink M, Stienen A et al. 2010 An explorative, cross-sectional study into abnormal muscular coupling during reach in chronic stroke patients *J Neuroeng Rehabil.* **7** 14.

[16] Houdijk H, Hoeve N, Nooijen C et al. 2010 Energy expenditure of stroke patients during postural control tasks *Gait Posture* **32** 321–326.

[17] Al-Mulla M, Sepulveda F and Colley M 2011 A Review of Non-Invasive Techniques to Detect and Predict Localised Muscle Fatigue *Sensors* **11** 3545-3594.

[18] Robertson J, Theberge J, Weller J et al. 2010 Low-frequency pulsed electromagnetic field exposure can alter neuroprocessing in humans *J R Soc Interface* **7(44)** 467-473.

[19] Amirifalah Z, Firoozabadi S, Shafiei S 2013 Local Exposure of Brain Central Areas to a Pulsed ELF Magnetic Field for a Purposeful Change in EEG *Clinical EEG and Neuroscience.* **44(1)** 44-52.
[20] Hakansson N, Hull M. 2009 Muscle Stimulation Waveform Timing Patterns for Upper and Lower Leg Muscle Groups to Increase Muscular Endurance in Functional Electrical Stimulation Pedaling Using a Forward Dynamic Model *IEEE T Bio-Med Eng* **56(9)** 2263-2270.
[21] Milanović S, Filipović S, Blesić S et al. 2011 Paired-associative stimulation can modulate muscle fatigue induced motor cortex excitability changes *Behvioural Brain Research* **223** 30–35.
[22] Das S, Kumar S, Jain S et al. 2012 Exposure to ELF- magnetic field promotes restoration of sensori-motor functions in adult rats with hemisection of thoracic spinal cord *Electromagn Bio Med* **31(3)** 180-194.
[23] Liu C, Zhu J, Li J et al. 2013 Functional Magnetic Stimulation System and Pulsed Magnetic-Field Effect on Peripheral Nerve *IEEE T Magn* **49(5)** 1853-1856.
[24] Darabant L, Plesa M, Micu D et al. 2009 Energy efficient coils for magnetic stimulation of peripheral nerves *IEEE T Magn.* **45(3)** 1690-1693.
[25] Troiano A, Naddeo F, Sosso E et al. 2008 Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale. *Gait & Posture* **28** 179–186.
[26] Berchicci M, Menotti F, Macaluso A et al. 2013 The neurophysiology of central and peripheral fatigue during sub-maximal lower limb isometric contractions *Front Hum Neurosci*. **7(135)** 1-10.
[27] Ravier P, Buttelli O, Jennane R et al. 2005 An EMG fractal indicator having different sensitivities to changes in force and muscle fatigue during voluntary static muscle contractions *J Electromyogr Kinesiol.* **15(2)** 210-221.
[28] Hussain M, Reaz M, Mohd-Yasin F et al. 2009 Electromyography signal analysis using wavelet transform and higher order statistics to determine muscle contraction *Expert Systems.* **26(1)** 35-48.
[29] Roman-Liu D, Konarska M 2009 Characteristics of power spectrum density function of EMG during muscle contraction below 30%MVC *J. Electromyogr Kinesiol* **19(5)** 864–874.
[30] González-Izal M, Malanda A, Gorostiaga E et al. 2012 Electromyographic models to assess muscle fatigue *J Electromyogr Kinesiol* **22** 501–512.
[31] Gazzoni M, Farina D, Merletti R 2001 Motor unit recruitment during constant low force and long duration muscle contractions investigated with surface electromyography *Acta Physiol Pharmacol Bulg* **26(1–2)** 67–71.
[32] Hagberg M 1981 Work load and fatigue in repetitive arm elevations *Ergonomics* **24(7)** 543–555.
[33] Meigal A, Rissanen S, Tarvainen M 2009 Novel parameters of surface EMG in patients with Parkinson’s disease and healthy young and old controls *J Electromyogr Kinesiol* **3(19)** 206–213.
[34] Angkoon P, Franck Q, Sylvie C et al. 2013 EMG feature evaluation for improving myoelectric pattern recognition robustness *Expert Systems* **40(12)** 4832–4840.
[35] Moon H, Kim C, Kwon M, et al. 2014 Force control is related to low-frequency oscillations

in force and surface EMG *Plos one* **9 (11)** (e10920211) 1-9
[36] Neto O, Baweja H, Christou E 2010 Increased voluntary drive is associated with changes in common oscillations from 13 to 60 Hz of interference but not rectified electromyography. *Muscle Nerve* **42(3)** 348–354
[37] Yoshitake Y, Shinohara M 2013 Low-frequency component of rectified EMG is temporally correlated with force and instantaneous rate of force fluctuations during steady contractions *Muscle Nerve* **47(4)** 577–584
[38] Kumar S, Mital A 1996 Electromyography in ergonomics: Taylor and Francis Ltd. *Universitas Muhammadiyah Surakarta* London UK.
[39] Bilodeau M, Arnsenaut A, Gravel D, Bourbonnais D 1990 The influence of an increase in the level of force on the EMG power spectrum of elbow extensors *Eur J Appl Physiol.* **61** 461–466.
[40] De Luca C and Erim Z 1994 Common drive of motor units in regulation of muscle force *Trends Neurosci* **17** 229–305.
[41] Calder K, Stashuk D, McLean L 2008 Physiological characteristics of motor units in the brachioradialis muscle across fatiguing low-level isometric contractions *J Electromyogr Kinesiol* **18** 2–15.
[42] Xie H, Guo J, Zheng Y 2010 Fuzzy approximate entropy analysis of chaotic and natural complex systems: detecting muscle fatigue using electromyography signals *Ann Biomed Eng.* **38(4)** 1483–96.